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Title

Governance and technological change: the effects of regulation in medical devices

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Abstract

Regulatory frameworks are a key institutional instrument for governance of change in socio-technical systems. One of the main problems in the extant literature on the role of regulation in innovation systems is that it assumes a static framework, often overlooking the dynamic relationship between innovation and regulation. In this chapter we show the dynamic interaction between US regulation in medical devices and the technological evolution of a surgical implant, the hip prosthesis, first introduced in the market in the early 1970s’. We suggest that the burdensome regulatory requirements imposed on the deployment of radical innovations in medical devices have led to the exhaustion of the search path for safe incremental innovations: as hip prosthesis have entered the mature stages of their technological evolutions, incremental improvements have become riskier and have ultimately failed.

Keywords

Governance, medical devices, incremental innovation, innovation patterns.

UAM-Accenture Chair

1. Introduction.

Any process of technical change carries with it an element of uncertainty: market responses are unpredictable, technologies may not work as expected and they may have unforeseen consequences. Such uncertainty occurs both when changes relate to a specific technology operating within a given innovation or socio-technical system, or when the changes are more profound and affect the whole system. Managing such uncertainty becomes one of the functions of a governance system, and in particular of the governance of processes of technological change. One of the instruments of such systems of governance is the development and implementation of regulatory frameworks. By focusing on regulatory framewoks, this paper focuses on one of the four pillars of the analysis of the governance of change in innovation systems identified by Borrás and Edler (2012): the "instrumentation of the governance of change". We see regulation as a form of governance instrument, shaping the ways in which actors involved in the innovation process develop, implement and use innovations. We understand regulatory frameworks as arrangements of "legally binding formal regulations which constrain and regulate interaction" in innovation systems (Borrás and Edler, 2012). In other words, regulatory frameworks affect the way in which actors involved in innovation processes coordinate their activities, they "guide the search" of innovations systems (Hekkert et al. 2007),[1] and shape the direction of technological change and the evolution of innovation systems.

One of the main problems in the extant studies of the role of regulatory frameworks in innovation systems is that they typically assume a static framework (Kemp, 1998; Blind, 2004, 2010), overlooking the dynamic nature of the interaction between regulation and innovation[2]. Hekkert et al. (2007) argued that this dynamic deficit is shared by the broader research on innovation systems: the analysis of the structural complexity of national, regional, sectorial or large-technological systems levels leaves little space for the detailed account of dynamic change. "Even though [the innovation system] framework is based on theories such as interactive learning and evolutionary

[1] An example of "guide of search" function in innovation systems is environmental regulation, which sets the goals of many fields of industrial innovation (Blind, 2010). Regulation performs this function together with other institutional structures derived from softer norms or values (Bergek et al., 2008).

[2] Until now, the literature on the relationship between regulation and innovation has mostly stressed the impact of regulation on innovation intensity, measured typically through R&D expenditure and patent counts (Vernon, 2005; Gerard and Lave, 2005; Golec and Vernon, 2010).

economics, most analyses of innovation systems are quasi-static in character. There is a focus on comparing the social structure of different innovation systems (actors, their relations, and institutions) and, thereby, explaining the differences in performance. Less emphasis is put on the analysis of the dynamics of innovation systems." (Hekkert et al., 2007:414). Instead, the "micro" level of analysis facilitates the study of innovation dynamics, overcoming these static frameworks by directing the analysis to specific "micro" technological fields or product technologies as in the Technological Specific Innovation Systems or Technical Innovation Systems approaches. Further, the study of dynamics of technological knowledge at the product level can benefit from the insights offered by one of the most important research traditions in Innovation Studies in the last three decades (Martin, 2012): Product Life-Cycle Theory (PLT).

In this work we draw on insights from PLT to help us analyse the dynamic interaction between US regulation in medical devices and innovation in a Technological Specific Innovation System built around a medical product (hip prosthesis) developed originally in late 60's. We will argue that US regulation is based on a crucial distinction between incremental and radical innovation, but does not consider that throughout the life cycle of a product such distinction does not remain fixed. We will suggest that in the hip prosthesis case this static regulatory division between radical and incremental innovation has led to recent attempts to engage in riskier, albeit incremental solutions, which ultimately failed. This outcome is somewhat paradoxical. Regulatory frameworks in medical devices were developed mainly to reduce the potential risks to patients of new technologies; they emerge as a governance tool to manage the uncertainties associated to new developments. Yet, we will show how the regulatory approach taken in the US has led to a specific form of technological change: incremental and, after a point, increasingly risky.

Next section provides a theoretical grounding for our proposition that riskier incremental innovations could in fact characterize late stages in some Technological Specific Innovation Systems[3]. Our argument will be anchored in recent complexity thinking about Product Life-Cycle, and it will consider the regulatory framework as a crucial variable in the later stages of the cycle. Section Three will try to flesh out these

[3] We use the term Technological Specific Innovation System introduced by Hekkert et al. (2007) because it can encompass the specificity of technological knowledge at the product level. The maybe more popular term of Technological Innovation Systems "usually refers to the notion of "Large Technological SystemsT (LTS)", introduced by Hughes" (Hekkert et al., 2007: 416)

ideas in the context of the technological history of hip prosthesis, which in our interpretation have been influenced decisively by the current US Medical Device Regulation. The last section proposes, under the light of the hip prosthesis case, avenues for further theoretical and empirical research.

2. Innovation Dynamics and Product Life Cycle Theory (PLT)

Although the roots of PLT are based on research on market entry barriers (Mueller and Tilton, 1969) and international trade theory (Vernon, 1970), the canonical formulation of the theory is anchored in Innovation Management, as the seminal works of Abbernathy and Utterback (1975; 1978) were originally concerned about which kind of innovation (radical or incremental) would have more possibilities of success during the market life of a particular industrial product. In its most popular form, heavily influenced by evolutionary thinking, the theory distinguishes essentially two innovative stages in product life cycle. In the early phases of the development of a product most innovations are radical and generate great product variety, as there is a high uncertainty about the characteristics of the new technology. As the cycle advances, from this variety a "dominant design" is selected and improved incrementally until a new cycle of radical innovation begins (Figure 1 shows a representation in a classic article of Anderson and Tushman, 1990). The most commonly used example to illustrate the PLT is the early history of automobile (Clarck, 1985): while in 1900, at the beginning of its development, three radically different solutions were present in the market with a comparable share (electric, gasoline and steam engines), in 1920 the gasoline engine had been selected as the 'dominant design'; since then, incremental innovations have been improving this dominant design.

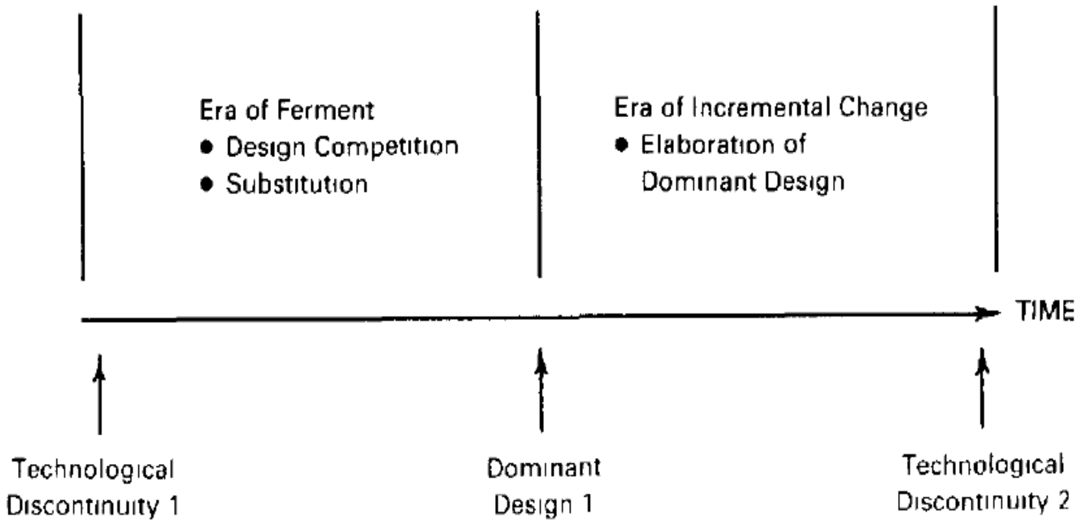

Figure 1. Innovation in product life-cycle (Anderson and Tushman, 1990)

Murmann and Frenken (2006:944) warned than when analyzing product life-cycles we must distinguish between the nature (incremental or radical) of technological change and the magnitude of social impact that such technological changes trigger. Probably due to its intellectual sources, anchored in Business Management, PLT studies have typically equated social impact with the competitive implications for firms of technological change (radical or incremental).[4] Yet the social implications of product life-cycles go beyond firm dynamics and market exit and entry rates: importantly for the role of regulation in innovation, the changing relationship between radical and incremental innovation through a product life cycle affects the risk in the adoption of new products.

The relationship between the type of technological change and the increase in risk is not direct and linear. First, in complex systems catastrophic events can be triggered by

[4] These competitive consequences refer usually to the exit and entry rates of firms during the life cycle: in the initial stages, new opportunities are reflected in a growing rate of entries, a small rate of exits and thus a rapid growth in the population of firms. When the dominant design appears, only a small number of firms can achieve economies of scale, setting high entry barriers, thus inducing a high number of exits and a small rate of entries, triggering a “industry shake-out” (Gort and Klepper, 1982). Again, the classic example is the automobile industry: in 1920s, two decades after the beginning of the cycle, more than 250 companies competed in the market; after the industry shake-out created by the emergence of the Ford T as “dominant design” and the economies of scale achieved by Fordist manufacturing techniques, less than 20 companies remained (Klepper, 1997).

small changes in one specific component -as in the O-ring failure of the Challenger shuttle catastrophe (Perrow, 1990; Reason, 1999)-. Similarly, literature on medical innovation (see Consoli and Mina, 2009, for a review) has showed that the relationship between body and technology is so complex[5] that improvements in technology cannot be linearly related with risk reductions.

Complexity theory has also used evolutionary arguments to build a dynamic understanding of the relationship between innovation and risk. Borrowing from evolutionary biology the notion of "landscape", some authors (Dennet, 1994; Frenken, 2006; Kaufmann, 1993) have proposed that incremental innovations can be conceived as local evolutionary searches[6] in a landscape where the neighborhood topology is determined by the similarities of the related technologies and the heights of the landscape are the performance values of each technology (Figure 2); performance values can be very different –creating a *rugged* landscape (Kaufmann, 1993)- even in the same technological neighborhood, as the interaction of different elements of the artifact could have huge effects in performance with even an incremental change in one of its elements (Frenken and Nuvolari, 2004). Following this logic, if we consider safety as one "service" dimension of technological performance (Lancaster, 1966; Frenken, 2006), an incremental search on a local but rugged "safety" landscape can lead to a severe technological failure.

This gives us already some clues about the possible dynamic relationships between innovation and risk regulation through a product life cycle. If a regulation is based on the assumption that the magnitude of technological change is directly and linearly related with increases in risk, it will place more burdensome regulatory requirements to radical innovations and less demanding ones to incremental innovations. This would creates incentives for innovators to explore the local landscape of technological possibilities (focus on incremental innovation), although, if this landscape is "rugged" small changes can generate considerable and negative effects on safety. Furthermore, as "leapfrogging" in the landscape in search of radical innovations (from A to B in Figure 2) is penalized by regulation, technological discontinuities will become rarer and product life cycles will tend to be longer (Figure 1). The implication here is that

[5] Typical complex phenomena in this field are for example side effects emerging suddenly several years after the therapeutic act (Gelijins and Rosenberg, 1994).

[6] Which are evolutionary in the sense that uncertainty is so pervasive in innovation that searches are partially "blind" (Campbell, 1960; Nelson and Winter, 1982).

innovators will continue its incremental search in the same local neighborhood, even in the most rugged and risky terrains (the valleys next to B in Figure 2, right). Thus, regulation can lead to "exhaustion" in the search for safe incremental innovations in late stages the life cycle: incremental search will continue even if it is around a "peak" of risk in the landscape. In the next section we will further explore this idea using the regulatory and technological history of hip prosthesis.

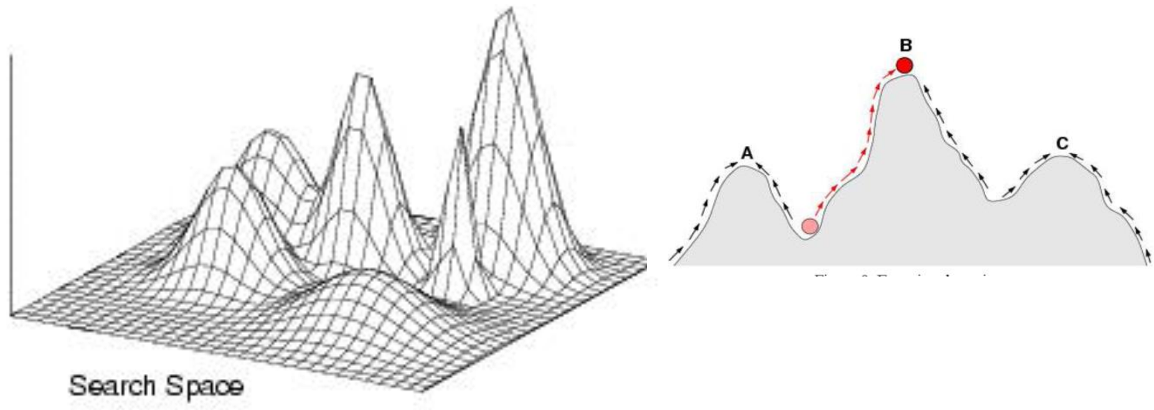

Figure 2. Left, a three dimensional landscape. Right, incremental and radical search in a two dimensional landscape.

3. The Hip Prosthesis Case

3.1 The US Medical Device Regulatory System

We will begin with a broad review of the regulatory environment for hip prosthesis in US. Historically, the 1976 Medical Device Act is conceived as a delayed effect of the Thalomide disaster in 1961. Reacting to this disaster, in 1962 drug regulations were enforced, but the different nature of medical devices delayed until 1976 the approval of a comprehensive regulation of these technologies (Foote, 1992). Before 1976, US medical devices were not subjected to any premarket review (Anderson, 2006).

The 1976 Medical Device Act introduced two different sets of regulatory requirements for innovations. When a device is classified as a radical innovation (i.e: not "substantially equivalent" to any pre-1976 device or to any post-1976 device already approved for market use) it has to pass a premarket clinical testing process which can cost millions of dollars and take an average of four years to complete (Foote, 1992). However, if the device is considered an incremental innovation ("substantially equivalent" to already approved devices or to pre-1976 devices) it can be introduced into regular use without premarket clinical testing through the so called 510k process, where only laboratory trials with synthetic models are required. Manufacturers start the 510k process claiming the similarity of their products to a specific "predicate device" (i.e., already approved devices or pre-1976 devices) and the Center for Devices and Radiological Health of the FDA decides whether to classify the new device as "substantially equivalent" to its predicate (IOM, 2011).[7]

It has been claimed that this regulatory environment reduced notably the innovativeness of US medical devices industry and delayed the introduction of radical improvements in the US market (Miller, 2002), by making it more costly to achieve radical improvements in medical devices. An early study on 62 medical products and 26 firms in the sector seemed to confirm this claim (Hauptman and Roberts, 1987).

The history of hip prosthesis development since 1970's also seems to confirm this assertion. A growing literature has identified the development of new materials as a key source of innovation for medical devices (Barberá et al., 2011; Barberá and Consoli, 2012; Morlacchi and Nelson, 2011; Mina et al., 2007; Consoli and Ramlogan, 2008). In the field of hip prosthesis, the introduction of bioceramics has been claimed as one of the most important innovations, as the friction of ceramic artificial articulations creates less wear debris than the traditional materials used in hip prosthesis, like metals and plastics (Anderson et al., 2006). Since the 1980's, several ceramic prosthesis have been introduced into clinical use in Europe. In the US, however, these prosthesis were not

[7] Although the European environment is more complex, generally speaking there has not been any systematic requirement in Europe for premarket clinical testing for hip prosthesis innovations until 2009. Until 1998 each country had its own regulations, and many of the most important countries in hip prosthesis development (except France from 1992 to 1998) did not include any requirement for premarket clinical testing of new designs. From 1998, hip prostheses were classified as a Type II device in the unified European regulatory framework, a class of devices that did not require premarket tests (Faro and Huiskes, 1992; Chai, 2000). In 2009, hip prostheses were reclassified as a Type-III device requiring premarket clinical testing if the Notified Body in charge of the approval process considers it necessary.

susceptible to be approved without premarket testing (contrary to incremental innovations in metal and plastic prosthesis, considered as "substantially equivalent" to hip designs commercialized before 1976). It was not until 2005 that the first ceramic prosthesis was commercialized in the US, after fulfilling the premarket clinical testing requirements (Kurtz and Ong, 2009).

3.2 Regulation and exhaustion of innovation.

Now we can come back to the argument developed in section 2; there, we have argued that a burdensome regulatory framework imposed on radical innovations can exhaust the search of safe incremental innovations in late stages of a product life cycle. As radical changes are discouraged by onerous regulatory obligations, the technological discontinuity that could start a new cycle of "fresh" search of safe incremental innovations is delayed; instead, there is a continued search for incremental innovations in the late stages of the product cycle exhausting all possible avenues for safe incremental innovation, thus leading to the pursuit of riskier incremental changes.

We argue that a recent failure in incremental innovation in hip prosthesis that had attracted media (Meier, 2011a,b,c; Meier, 2010) and institutional (IOM, 2011) attention could be interpreted as a signal of this safety exhaustion in incremental search. In 2005, a new prosthesis with *bigger* prosthetic femoral heads was classified as "substantially equivalent" to prior and smaller standard femoral heads for hip prosthesis. This small head standard size was established in the 70's as an trade-off between the anatomical head size and the problems caused by wear debris in the artificial articulation; wear debris originated in the friction of the articulating components can migrate to the implant-bone interface and can cause an allergic reaction and implant loosening. This mechanism is the most common mode of failure in hip prosthesis. The chosen standard size was smaller than the anatomical femoral head, and thus had a higher risk of dislocation, as dislocation distance increases with the reduction of head size; at the same time, however, smaller head size causes fewer loosening failures since the head's size is inversely correlated with the amount of debris generated by friction (Figure 3). Until the early 90s, when wear debris was identified as the underlying mechanism behind many implant failures, the nature of the allergic mechanisms that cause implant loosening was not known (Kurtz, 2009; Anderson et al., 2006).

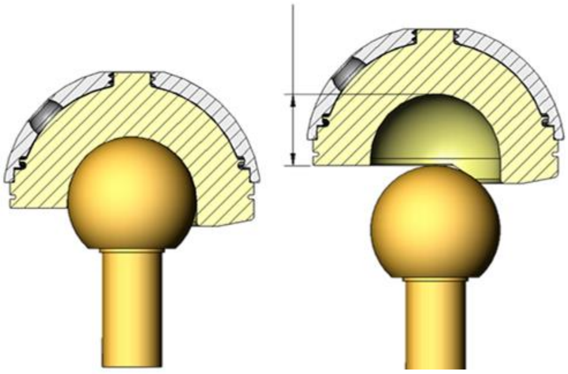

Figure 3. Less diameter of femoral head, bigger risk of dislocation (left). Less diameter of femoral head, lesser amount of debris generated by friction (right).

In 2005 (about 35 years after the introduction in the market of hip prosthesis) a US company developed a new design with bigger prosthetic femoral heads: the rationale for the new bigger head design was based in improvements in manufacturing of existing metallic materials, which allegedly reduced wear debris in the artificial hip articulation even with larger head diameters (which have less risk of dislocation than the smaller standard head). The device was classified by the FDA as "substantially equivalent" to the prior smaller heads design (FDA, 2005).

Apparently, this incremental improvement solved the trade-off between wear debris and dislocation risk. However, in 2010 (after 5 years of regular use), an important amount of early failures of the prosthesis caused by allergic reaction to debris were identified and the prosthesis was retired from the market in 2011 (Langton et al., 2010; Graves, 2011). It is estimated that the failure of the prosthesis will affect 30.000 patients, who will have to be re-operated (Meier, 2011a).

The bigger head design was a step towards a solution to a persistently ill-understood problem -the allergic reaction provoked by wear debris- by means of an incremental innovation in the manufacturing of existing materials. The unintended and ill-understood interaction between two presumably independent elements of the hip prosthesis system (the artificial articulation where the wear debris is generated by friction and the bone-implant interface where the debris migrates and provokes the allergic reaction responsible for the loosening of the implant, Figure 3, right) caused that even an incremental change in the diameter of the head could have dramatic consequences in safety. Moreover, this risky incremental change happened in 2005, more than 35 years after the product cycle started with the original designs of hip prosthesis. Although we have seen that the US medical device regulation has probably influenced the delayed introduction in US of radical innovations like the use of ceramic materials (which arrived to the US market also in 2005), this does not mean that research efforts were absent. A keyword search in PatStat database give us 683 US patents related to hip prosthesis technology for the 1976-2005 period (from the approval of the Medical Device Act to the failure of "bigger heads" incremental innovation). As the radical or incremental character of patents cannot be derived from available patent databases, we do not know the innovative degree of these patents. In any case, they confirm a continuous inventive activity during that period which may have led to an "exhaustion" of innovation in early years.

4. Discussion

Our brief account of the regulatory and technological history of hip prosthesis suggests that an incremental search in a highly uncertain and risky terrain could be an outcome of a search exhaustion at the late stage of product-life-cycles. Supported by theoretical work on the nature of risk landscapes and product life-cycels, we interprete the failure of the "bigger heads" incremental innovation after 35 years of extensive use of and continued research on hip prosthesis as a case of search exhaustion. Our story also suggests that search exhaustion has been intensified by the US regulation in medical devices, which incentivizes incremental innovation regardless of the dynamic character of the product life-cycle.

More generally, this chapter has highlighted the need for a dynamic perspective understanding of innovation knowledge when dealing with regulatory instruments of governance. In the hip prosthesis case, this regulatory instruments seemed to "guide the search" within the US medical devices Technology Specific Innovation System towards incremental improvements, under the implicit assumption that incremental rates of innovation linearly induce incremental growth in risk. If incremental search exhaustion is a general property of the late stages of product life cycles, governance of change in these late stages (Stegmaier et al., 2012) could benefit from the lessons of the hip prosthesis case. To fulfill their risk-reduction function, regulatory frameworks instruments need to acknowledge the dynamic character of technological change, and be adaptable to the different implications of incremental search strategies in different stages of a product life cycle.

This opens a new set of research challenges. As Blind (2010: 238) put it, "a systematic analysis of the timing of regulation in the context of a whole innovation cycle is missing. Especially, the co-evolution of innovation and the regulatory framework has so far not been addressed". Our interpretation of the relationship between the US medical device regulation and the innovation dynamics of hip prosthesis is a first step towards addressing this gap. Our research suggests that regulation, as a form of instrumentation of the governance of change, needs to adapt to the technological characteristics of such change. That product life cycles have a bearing on the adequacy of some governance instruments to steer technological change towards some pre-specific goals (here the reduction of risks for patients) implies that the evolution and outcomes of a governance system for technological change do not depend solely on socio-political factors (structure and capability of the agents, legitimacy issues and learning processes) but also on the technological characteristics of the product families subjected to regulation.

Our analysis has focused on the "instrumental pillar" of governance. The case we have presented also has implications for the other "pillars" in the governance of change identified by Borrás and Edler (2012). Yet, the problems with prosthetic hip designs we have presented here are relatively recent and it is yet too early to assess how the role that the other pillars in the governance of change will come to play. For instance, the technological failures we have referred to are likely to have an effect on the legitimacy of governance structure; patients and institutions as the Institute of Medicine (a part of the US National Academy of Science) are questioning the regulatory systems that have so clearly failed to fulfill the objective of increasing safety and reducing risk. Yet, the way in which this legitimacy crisis will play up remains uncertain, as the industry had waged since the beginning of the crisis an aggressive campaign to discredit the report of the Institute of Medicine, which asked for stricter regulation (Meier, 2011a). The way the regulatory framework will be able to acquire legitimacy depends on the learning processes, but the lessons that the publics will draw from the events we have described and analyzed are not predetermined. There will be argument and debate and the regulatory policy that will emerge as more legitimate is not predetermined by the technological developments and the ensuing legitimacy crisis we are presenting here. The different pillars have their own dynamics and it is too early, in our case, to identify how the interactions among them will develop. We are still in the early phases of what we expect will be a crisis of legitimacy and an uncertain process of "learning" triggered by a problem generated by the way in which technological change occurs under a particular regulatory instrument. It is important to note, however, that an important element that emerges in the process of technological change we have described occurs because of a "given logic, which is not culturally or socially determined" (Bimber,1994: 84). In the "technological landscape" metaphor we have used, the "logic" of the "rugged" neighborhoods is created by the critical relationship between the size of the artificial hip prosthesis head and wear debris production. This is a purely technological relationship which is crucial to explain late failures of hip prosthesis. The way in which society will steer technological change to respond to this challenge will depend on the forms of learning and the types of regulation that will acquire legitimacy on the aftermath of a regulatory crisis. In our account, organizations and individuals create regulations using dubious assumptions about the relationship between innovation, risk and time; yet these assumptions may be persistent. Other kind of organizations and individuals have creatively followed the incentives posed by those regulations, discovering new incremental innovations until this form of search for innovations have become exhausted because of the technological characteristics of the landscape we have described. It is in the analysis of the social response to this crisis that the remaining "pillars" of technological change governance will come to play a role, which is so far unpredictable.

We have shown how such unpredictability has so far been rooted on scientific uncertainty about the mechanisms underlying the deleterious effect of wear debris. In our interpretation, this uncertainty made innovators unable to predict how riskily "rugged" was the technological landscape they were exploring. Notably, the risky explorations of the size-wear debris relationships happened late in the product-life cycle: it was only after various decades of prolonged search in other (and apparently characterized by less intense uncertainty) locations when innovators decided also to explore new designs with bigger heads. Although this exploration did only imply size variation, this incremental change drove the innovative agents to uncertain terrains which ultimately resulted to be intolerable risky. How public policy and, with it, technological change will respond to this problem is also unpredictable, not because of technological uncertainty, but because of the uncertain outcome of complex policy processes in which different policy stakeholders may draw different lessons from their experiences and propose different regulatory and technological solutions.

From our point of view, and from a more normative perspective, we would argue that our research suggests that safety regulations for incremental innovation may need to become more restrictive towards the end of a product life cycle. This recommendation is, of course, exceedingly difficult to implement in practice and is unlikely to be universally shared. In medical devices regulation terms, it could mean that the premarket clinical trials should be applied to every innovation (incremental or radical) and lighter regulatory frameworks -without premarket trials- should only be applicable, if at all, to incremental innovations in the mid-part of the product life cycle, when local search has not still exhausted safer incremental improvements. Normatively, such decisions call for a highly reflective system of governance: there is a need for continuous monitoring and learning, as the implications of technological change for the governance systems of such change are constantly changing with the levels of product maturity.

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